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Published in:
Proceedings of the 19th Coherent Laser Radar Conference, CLRC 2018

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Wind turbine rotor-effective wind speed estimated by nacelle-mounted Doppler wind lidars

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Abstract: Over the past two decades, research has demonstrated a substantial structural load reduction potential of lidar-assisted wind turbine controllers; especially for lidar-assisted pitch control, opening the possibility of lighter rotors and cheaper wind turbines. Knowing how well a lidar can estimate the rotor-effective wind speed (REWS) is an important aspect of designing an optimal pitch controller. This contribution investigates the inter-comparison between REWS estimated by a forward-looking nacelle-mounted lidar and the wind turbine itself. We present measurements from two experimental campaigns, where an economical and robust cw Doppler wind lidar is mounted on a heavily instrumented Vestas V52 turbine. The results indicate that the coherence between lidar and turbine estimated REWS is in agreement with analytical models. Also, the time delay between the two signals conforms to the expected results. This implies that the models used to design and optimize lidar-assisted pitch controllers match with experimental results.

Keywords: Wind turbine, rotor-effective wind speed, pitch control, nacelle lidar, wind energy

1. Introduction

Lidar systems mounted on the nacelle or inside the spinner of wind turbines are able to provide in-advance information about the incoming wind field in front of a turbine. Several controllers have been proposed to improve power production and/or mitigate structural loading; for an overview see [1]. Promising simulation results were demonstrated with a relatively simple feed-forward addition to the traditional feed-back speed controller in wind turbines [2]. An illustration is shown in figure 1. Disturbances in the incoming wind field v can be estimated based on lidar measurements and a feed-forward controller $\sum_{FF}$ can derive an additional pitch demand θ_{FF} that can be added to the feed-back demand before pitch actuation of the wind turbine WT. Such a controller could ideally completely compensate any disturbances in v that are affecting WT, however due to turbine modelling and lidar measurement limitation the performance is always non-ideal. In this study we will focus on the drawbacks

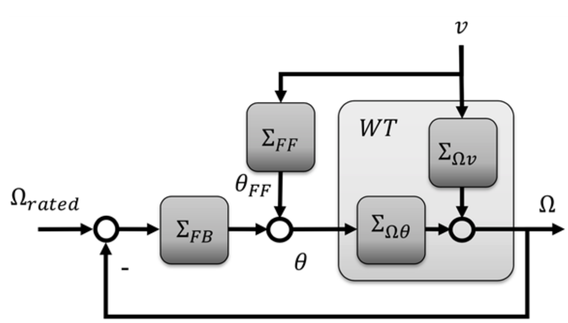

Figure 1. Example of a collective pitch feed-forward controller augmenting a traditional feed-back controller, from [2].

of estimating the rotor-effective wind speed (REWS) from lidar measurements. The REWS $v_{eff,R}$ is defined as the average of the longitudinal wind velocity u_x over the entire rotor plane

$$v_{eff,R} = \frac{1}{\pi R^2} \int_0^{2\pi} \int_0^R u_x(r,\theta) r dr d\theta \ ,$$

where R is the rotor radius.

Coherent wind lidars can measure the frequency shift according to the optical Doppler effect of light backscattered on moving aerosols levitated in air. For a cw lidar the line-of-sight (LOS) measurement $v_r(\boldsymbol{r})$ at focus $\boldsymbol{r}$ is a convolution integral between the weighting function $L(s) = \frac{1}{\pi}\frac{z_R}{z_R^2+s^2}$ and the LOS component of the wind velocity $\boldsymbol{u}$

$$v_r(\boldsymbol{r}) = \int_{-\infty}^{+\infty} L(s) \boldsymbol{n} \cdot \boldsymbol{u}((s\boldsymbol{n}+\boldsymbol{r}))\, ds \ ,$$

where z_R is the Rayleigh length and $\boldsymbol{n}$ is the beam unit vector. This implies that only one component of $\boldsymbol{u}$ can be measured and a low-pass filtered signal compared to a point measurement. Together with the discreet number of measurement points and the evolution of turbulence between measurement and rotor plane, these are the imperfections of lidar measurements when estimating $v_{eff,R}$.

To evaluate the correlation between REWS estimated from the turbine and the lidar it is important to know the coherence between the two signals, which is defined as

$$\gamma_{RL}(k) = \frac{|S_{RL}(k)|^2}{S_{RR}(k) S_{LL}(k)} \qquad (1)$$

with $S_{ij}(k)$ is the cross-spectrum between signal i and j as a function of the wave number $k = \frac{2\pi}{f}$; R refers to the turbine and L to the lidar. The spectra are calculated in blocks of 600 s. Further the coherence determines the minimum achievable measurement error [3]. Here we present measurements of $\gamma_{RL}(k)$ for two nacelle-mounted lidars manufactured by Windar Photonics A/S[1].

2. Theoretical Model

The coherence in eq. (1) can also be calculated analytically by using the Kaimal turbulence spectra and the exponential spatial coherence model defined in the IEC 61400-1 Ed.3 standard. Details can be found in [3].

3. Experimental Setup

An experiment using two lidars by Windar Photonics A/S was conducted at the Risø test site. The lidars were mounted on the nacelle of a Vestas V52 with 850 kW of rated power. The systems scan at discrete focus points on a cone with 2 or 4 beams, see figure 2. More information can be found in table 1.

To estimate REWS from lidar measurements no vertical components and a perfectly aligned turbine were assumed and the average of the n LOS components ($n \in \{2,4\}$) was calculated

$$\hat{v}_{eff,L} = \frac{1}{n\cos(\alpha)} \sum_{i=1}^{n} v_{r,i} \ ,$$

where α is the half-cone opening angle. The sampling rate was 1Hz. The lidar measurements have also been corrected for turbine induction according to the theory of [4].

[1] Company webpage: http://www.windarphotonics.com/

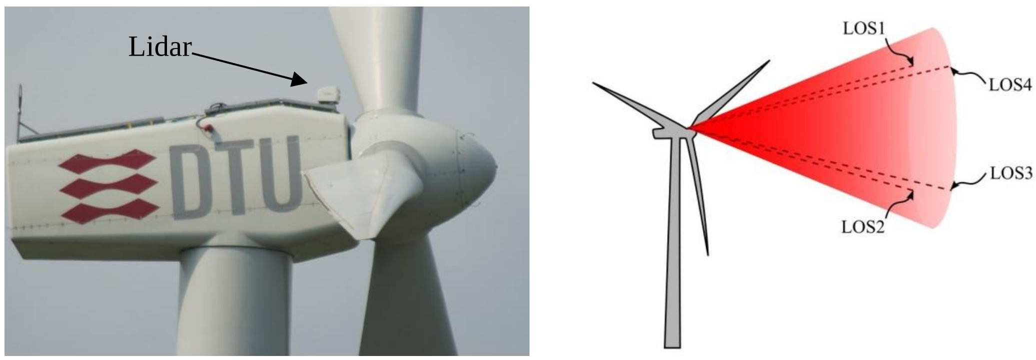

Figure 2. Photo and illustration of the installation of the 4-beam lidar at the Risø test site.

To measure $v_{eff,R}$ from turbine data the method in [5] was followed. Measurements of pitch angle, rotor speed, low-speed shaft torque and air density were used in combination with the pre-calculated power coefficient surface to derive $\hat{v}_{eff,R}$ by applying conservation of angular moments for the drive-train.

Table 1. Overview of the measurement campaign

Quantity	2-beam lidar	4-beam lidar
Focus Distance (along LOS) L_f	37 m	62 m
Half-cone opening angle α	30º	18°
Measurement period	Mar-May 2016	Oct – Dec 2016
Nr. of useable 10Min averages	2043	1152

4. Results

The result for the measurement coherence is presented in fig. 3. It can be seen that for small wave numbers coherences for both lidars approach unity. As expected, the coherence for the 2-beam lidar drops at lower wave numbers compared to the 4-beam lidar since only measurements at two points over rotor plane are measured. It can also be seen that the measurement agree well with the theoretical calculations. The 4-beam lidar results show larger deviation from the theory, which could be attributed to the larger

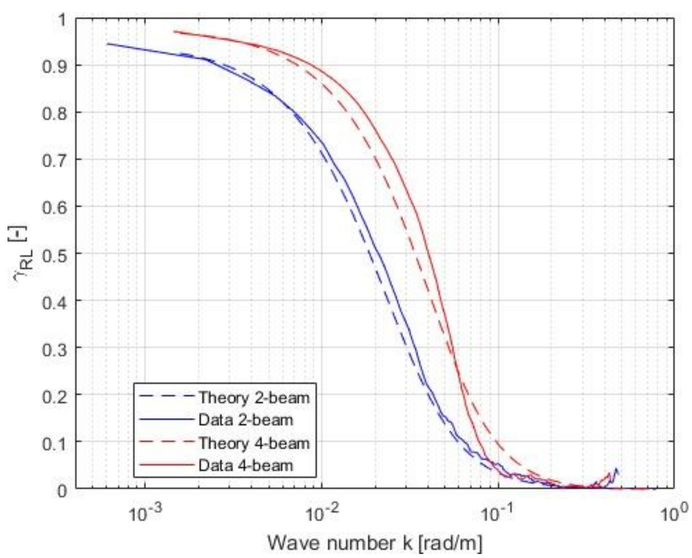

Figure 3. Coherence between lidar and turbine estimated REWS as function of wave number.

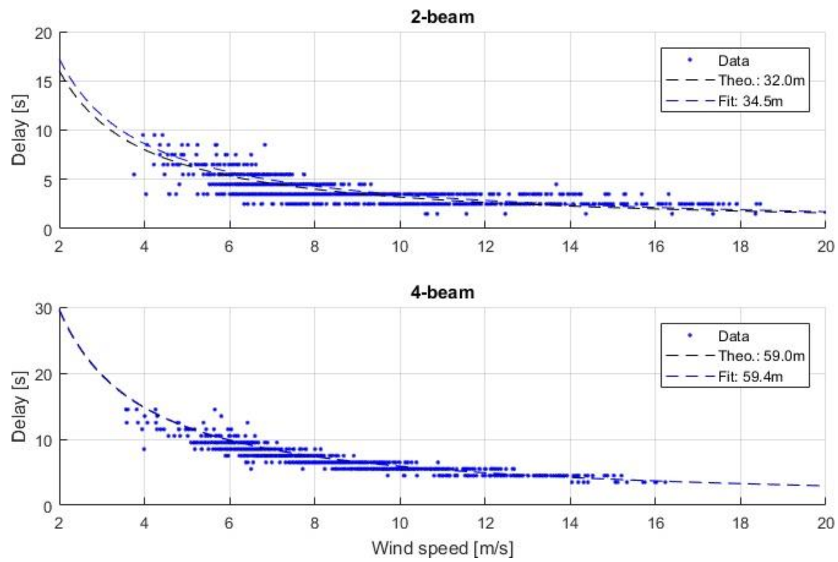

Figure 4. Measured time delay between turbine and lidar estimated REWS as function of wind speed.

distance between measurement and rotor plane (see table 1). The effect of turbulence evolution, which is not considered in the theoretical calculations, is bigger of larger distances.

Another important aspect for lidar-assisted pitch control is to predict when a disturbance that has been measured at the measurement plane will affect the turbine in the rotor plane. In order to do so, we assume that all fluctuations are advected with the mean wind speed (Taylor's frozen turbulence hypothesis). This mean wind speed can be estimated by taking a reasonable long average of the transversal wind speed component u_x. Here we used a 600 s average. The delay between the two signal Δt can then be calculated as

$$\Delta t(\overline{u_x}) = \frac{L_f \cos(\alpha)}{\overline{u_x}} \tag{2}$$

and it can also be estimated using the peak index of the cross-correlation between the two signals. The results are shown in fig. 4, where it can be seen that delays fit well to expected values. Likewise, a fit of L_f to eq. (2) shows that the delay speed can be predicted accurately by taking a 600s wind speed average.

In general, this study shows statistically how well lidar systems can estimate the REWS that affect wind turbines. The measurement results are in agreement with analytical models. This indicates that the theory models the underlying physics well and can be used to find optimal lidar configuration for lidar- assisted wind turbine pitch control.

5. References

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